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Considerations on providing the energy needs using exclusively renewable sources: Energiewende in Germany

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ABSTRACT

The share of renewables in the primary energy demand of Germany has increased from 1.3% in 1990 to 11.7% in 2013. The plans are to increase it further, by the year 2050, to 50% or even 100%, by carrying out the national Energiewende (energy change/switch) programme. In this paper we analyze the current energy scenario and recall goals of the Energiewende programme. We also identify infrastructural and technological bottlenecks which are likely to affect the programme execution. By doing so, the enormous scale of this national venture becomes apparent and it is clear that its execution will last for several generations and perhaps even for a century or two. Additionally, we introduce an idea of Exclusively Green Energy Communities (EGECs) as an Energiewende mile-stone. Due to the dimensions of the tasks, the energy change/switch programme will last for several generations and perhaps even for a century or two. Realization of this overwhelming national venture has to proceed through milestones and demonstration projects. We propose demo-projects, called Green Energy Communities (GECs), to examine with what efforts and under what constraints such communities can operate using exclusively renewable forms of energy.

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1. Introduction and objectives

Replacement of fossil and nuclear fuels with renewables has been going on in Germany for around twenty years. The share of renewables in the primary energy demand has increased from 1.3% in 1990 to 11.7% in 2013 [1–3] and the plans are to increase it further to 50%, or even 100%, by 2050 [4,5]. Thus, it is clear that in comparison to the current rate of energy conversion from renewables, a very substantial increase is needed to satisfy the energy demand of the nation using exclusively renewable sources. This, so called "Energiewende" (energy change/switch) programme, has found a wide acceptance in German society although the scale of the proposed changes is not ascertained and its complexity is not fully comprehended.

The objectives of this paper are to (i) analyze the current energy scenario in Germany, (ii) recall goals of the Energiewende programme, (iii) identify the infrastructural and technological bottlenecks which are going to affect the programme's implementation, (iv) underline the enormous scale of this national venture and define realistic timescales for its implementation, and (v) introduce Exclusively Green Energy Communities (EGECs) as an important Energiewende's milestone. The paper is constrained to technical aspects only and social and political arguments are not considered.

In what follows, we consider several types of renewables (solar, wind, biomass, hydro- and geothermal-energies) in the context of their applicability to substitute fossil fuels. To illustrate several points, we perform simple calculations (estimates) which are based on two kinds of data. To the first kind belong official data provided by the German Ministry for Economy and Technology (BMWi) and the German Ministry for Environment (BMU) and they are concerned with past and current energy statistics [1–3] as well as with projections and planning [4]. The second type data [5] includes projections and concepts which are being developed by the German Research-Association for Renewables (Forschungsverbund erneuerbare Energien – FVEE). The Association plays an advisory role to the Government in proposing energy plans which are then discussed within the Ministries and the Government.

During the Energiewende fossil fuels will remain important for a considerable period of time, although the ultimate goal is to abandon their usage perhaps as soon as 2050 [4,5]. In this paper we propose a 100% provision of a small local region with energy converted using exclusively renewable sources in order to gather necessary experience. Through such pilot or test projects, one can determine whether the proposed solutions are realizable as long-term options. Later on, we consider such a regional-area-unit which we name here as Exclusively-Green-Energy-Community (EGEC)

2. Current energy demand

2.1. Primary energy

In Fig. 1 the primary energy demand for Germany is shown to be 3890 TWh/a (14 EJ/a)[1] for 2013 with a 11.7% share of renewables. Fig. 2 shows that over the last twenty years the share of renewables increased from 1.3% in 1990 to 11.7% in 2013 with the most rapid increase occurring in the 2005–2013 period. The overall energy demand slightly decreased from 4140 TWh/a (14.9 EJ/a) to 3890 TWh/a (14 EJ/a). The current (2013) energy demand of 3890 TWh/a (14 EJ/a) corresponds to a yearly-averaged power of around[2] 443 GW. This slight decrease in the primary energy demand over the twenty-year period should be correctly understood. The continuously increasing energy demand per capita has been offset but the on-going process of improving the energy conversion efficiency (Power Stations, and Refineries) as well as the energy utilization efficiency (Industry, Commerce, Transportation, and Residential). These processes of energy efficiency improvements have been going on since the industrial revolution and for such "modern" terms like Energy-Efficiency-Increase or Energy-Efficient-Technologies are used. Fig. 2 also shows the strong dependence of Germany on the energy import since the 13.7 EJ primary energy demand for 2012, only 4.4 EJ (32%) was provided by the country's own resources.

In order to present the primary energy demand of Germany in an international perspective, Table 1 has been compiled using the data of US Energy Information Administration [7]. The amount of energy needed is enormous and in order to comprehend such large quantities we convert the amounts into an energy-equivalent cube of oil and list, in the fourth column of Table 1, the size of the cube per country. The World's primary energy demand amounts to 510 EJ/a. Germany's demand[3] of 14.3 EJ/a constitutes 2.8% of the World's figure whilst Germany's population makes up only 1.17% of the World's population. The fifth column contains the primary energy demand per capita showing that an average citizen of Germany, France, Switzerland and Japan needs around four tonnes of oil equivalent energy per annum. In countries like Canada, US, Kuwait and United Arab Emirates more than double amounts have being consumed whilst many African or South American nations function on one-tenth or less of this amount.

It is worth observing that the split of the primary energies into different fuels/sources (Fig. 1) for Germany is very similar to the one applicable to the US (see captions to Fig. 1); the split for 2013 is renewables 11.7% and 8%, nuclear 7.5% and 8%, crude oil 32% and 37%, and coal 24% and 19% for Germany and the US, respectively. The primary energy demand for the US is 7.7 times larger than that for Germany.

2.2. End-user energy

Primary energy (natural gas, crude-oil, coal, nuclear fuels, wind and solar energy) is converted in power stations into electricity, and in refineries and chemical plants into liquid and gaseous fuels to satisfy the energy demand for energy end-users. The energy demand for end-users amounts to around 65% of the primary energy demand and it slightly varies from year to year. For example, as shown in Fig. 3, for the year 2012, the amount of 2499 TWh (9 EJ) was consumed by end-users which for the primary energy demand of 3806 TWh (13.7 EJ), (see Fig. 2),

[1] Tera $(T)=10^{12}$; Exa $(E)=10^{18}$; 1 ThW = 0.0036 EJ.

[2] For 365 days/year and 24 h operation/day. For comparison; currently installed electrical power in Germany is 175 GW (see Table 2).

[3] See footnote a of Table 1.

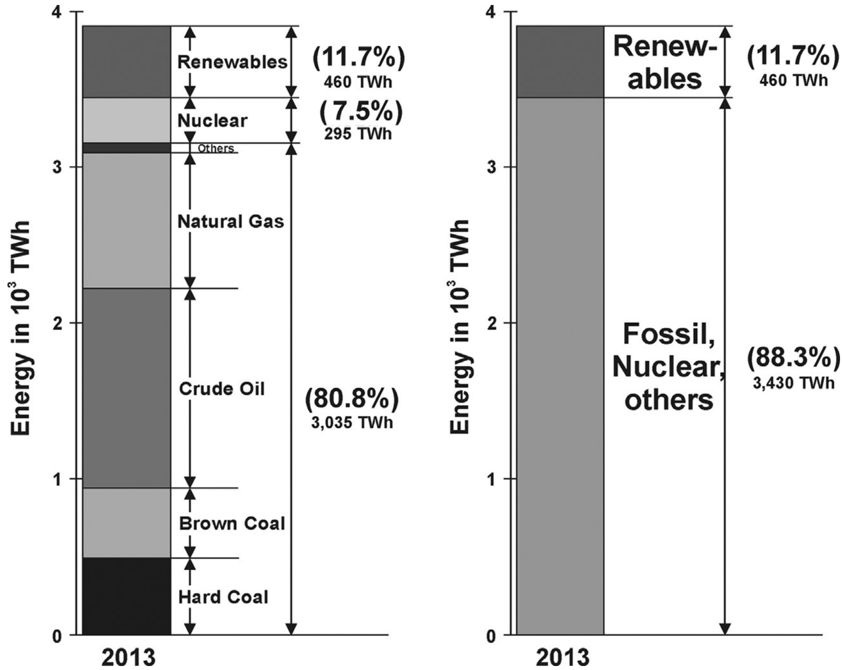


Fig. 1. Primary energy demand for Germany [2], total amount for 2013 is 3890 TWh = 14 EJ (for comparison the 2013 US figures [6] are total demand of 28,280 TWh/a (102 EJ/a) with the split: renewable – 8%, nuclear – 8%, natural gas – 27%, coal – 19%, and crude oil – 37%).

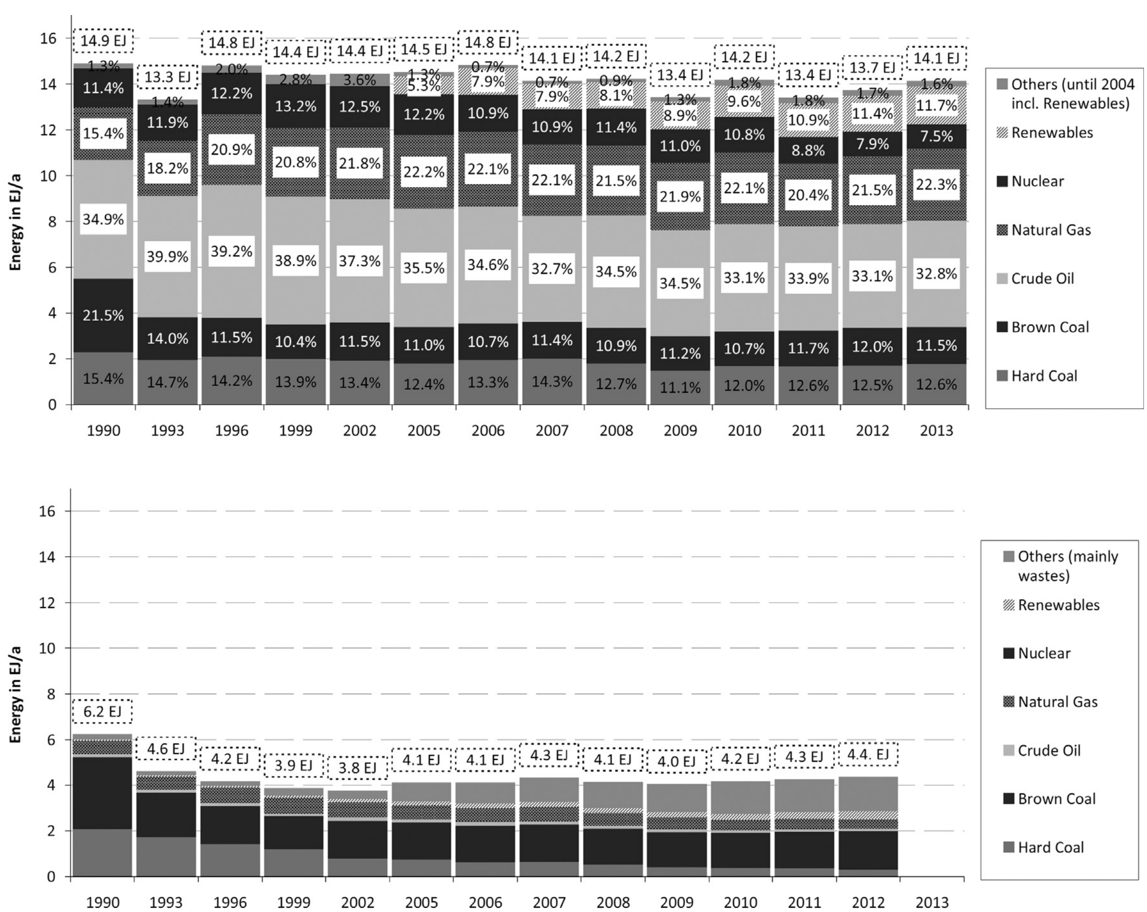


Fig. 2. Development of primary energy demand of Germany over the last twenty years (adapted from Ref. [1]). Top – primary energy demand; Bottom – energy demand covered by Germany's own resources.

corresponds to 65.7%. The end-user energy consumption of 2499 TWh corresponds to the average annual power of around 292 GW. The 36% losses occur mainly due to the electricity production in fossil fuels (conventional) power stations which operate with an average efficiency of around 38–40% calculated for the current energy-mix. Fig. 3 shows that the industry,

Table 1
Primary energy demand of selected countries for the year 2009 (compiled using data of the US Energy Information Administration [7][a]).

World/ continent/ country	Population in millions	Annual primary energy demand in EJ/a	Size of energy equivalent oil cube in m	Energy demand per person in TOE/a/person
World	6973.74	510	2298	1.74
Europe	739.17	85.5	1267	2.75
US	311.59	103	1349	7.87
Canada	34.48	13.8	690	9.55
Germany	81.73	14.3	698	4.17
UK	62.64	9.4	608	3.57
France	65.44	11.3	646	4.11
Sweden	9.45	2.21	375	5.56
Denmark	5.57	0.84	272	3.58
Italy	60.63	7.76	567	3.05
Poland	38.22	4.22	465	2.63
Czech Republic	10.56	1.63	338	3.66
Ukraine	45.71	4.99	491	2.60
Spain	47.19	6.44	535	3.25
Switzerland	7.91	1.39	321	4.19
Russia	141.93	28.4	878	4.77
China	1344.13	95.7	1316	1.69
South Korea	49.78	10.5	631	5.05
Japan	127.82	21.8	804	4.07
India	1241.49	23.0	818	0.44
Philippines	94.85	12.7	312	0.32
Indonesia	242.33	6.42	534	0.63
Australia	22.62	5.93	521	6.24
South Africa	50.59	5.8	517	2.73
Kenya	41.61	0.21	170	0.12
Ghana	24.96	0.20	167	0.19
United Arab Emirates	7.89	3.46	435	10.43
Turkey	73.64	4.28	467	1.38
Iran	74.80	9.56	611	3.04
Kuwait	2.82	1.32	316	11.14
Saudi Arabia	28.08	8.30	583	7.04
Brazil	196.66	10.90	638	1.32
Venezuela	29.28	3.38	432	2.75
Chile	17.27	1.28	313	1.77
Ecuador	14.67	0.55	235	0.89

LCV of oil = 42 GJ/tonne; TOE – tonne of oil equivalent; 1 EJ = 10^{18} J.

[a] There is some inconsistency in the energy data. For example, the above table which is based on the data of the US Energy Information Administration [7] lists 14.3 EJ/a as the energy demand for Germany for the year 2009 whilst the German source [3] (see Fig. 2) quotes a figure of 13.4 EJ/a.

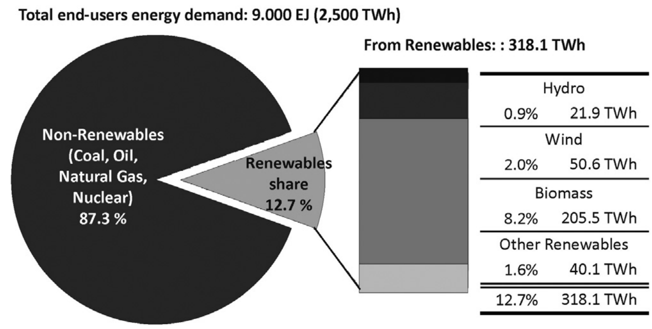
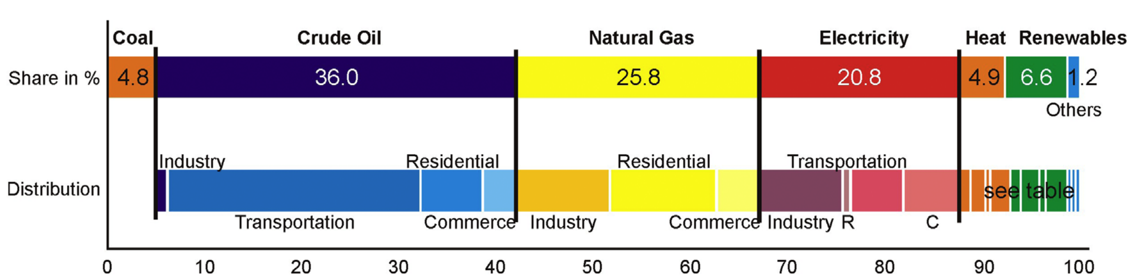


Fig. 4. Renewables share in the end-user energy demand (see Fig. 3) for Germany for the year 2012 (adapted from Ref. [3]).

Table 2
Share of fossil fuels, nuclear fuels and renewables in the 2011 gross electricity generation in Germany (compiled using data of Ref. [1,3]).

	Installed nameplate capacity in GW	Generated electricity in TWh	Availability factor	Share in gross electricity in %
Nuclear	12.7	108	0.97	**17.6**
Fossil fuels				**58.04**
Hard coal	30.2	112.4	0.43	18.33
Brown coal	24.9	150.1	0.69	24.48
Natural gas	23.9	86.1	0.41	14.04
Oil	6.4	7.2	0.13	1.17
Hydro	5.0	5.8	0.13	**0.95**
Geothermal	0.0075	Negligible	–	Negligible
Renewables				**19.41**
Wind on-shore	28.7	48.3	0.19	7.88
Wind off-shore	0.33	0.57	0.20	0.09
Solar	25.0	19.6	0.09	3.20
Biomass	5.4	32.8	0.69	5.35
Hydro	5.6	17.7	0.36	2.89
Others including waste	6.4	24.5	0.44	**4.0**
Total	**174.5**	**613.1**	**0.40**	
Export	–	6.3	–	**1.0**



End-users energy demand in 2012 for Germany	EJ	TWh	%	Coal	Oil	Gas	Electr-icity	Heat	Renew-ables	Others
Industry (I)	2.599	722	28.9	4.1*	0.9*	10.4*	9.0	1.9*	1.4*	1.2*
Transportation (T)	2.571	714	28.6	0.0	26.2	0.4	0.7	0.0	1.3	0.0
Residential (R)	2.431	675	27.0	0.6	5.6	10.1	5.5	1.9	3.4	0.0
Commerce (C)	1.397	388	15.5	0.2	3.3	4.9	5.6	1.1	0.5	0.0
Total	8.998	2,499	100	4.8	36.0	25.8	20.8	4.9	6.6	1.2

** Sum of non-electrical (=chemical) energy in industry: 19.8%*

Fig. 3. End-user energy demand in Germany for the year 2012 (adapted from Ref. [1]).

transportation and residential sector consumed around 28% of the end-used energy demand each while the remaining 15% was used by commerce. Around 36% was consumed as transportation fuel (petrol, diesel, and aviation fuel) while 20.8% as electricity produced using fossil and nuclear fuels as well as renewables. The renewables' share was mainly used as electricity (around 6.6%) in the residential sector (3.4%) and in industry (1.4%) as fuels, and in transportation (1.3%) as bio-diesel. Fig. 4 shows how the 12.7% share of renewables was split into hydro, wind, biomass and others (including solar).

2.3. Electricity

Electricity deserves extra comments since debates concerning Energiewende often focus on this form of end-user energy. In 2012, the country used around (0.208×2499) 520 TWh of net electricity which makes 20.8% of the end-used energy (see Fig. 3) with industry (9%), residential (5.5%) and commerce (5.6%) being the main consumers; only 0.7% was used in transportation, mainly on railway tracks. In Table 2 we show the gross[4] electricity generation for the year 2011 since the data for 2012 are still incomplete [1]. In addition to the installed name plate capacities and the amount of electricity generated, the table also includes availability factors which are calculated as the ratio of the electricity generated to the amount which could be generated, if the installed capacity would be operational continuously throughout the year, it means operational for (365 days $\times$ 24 h) = 8760 h. Both coal-fired and nuclear power stations provide most of the baseline demand whilst natural-gas and oil-fired power stations are used in peak-demand periods. Although the electricity market regulators give preference to green electricity, the availability factors for renewables remain low with a notable exception for biomass. This is because the factors are determined by the availability of solar radiation and wind. The availability factors for fossil and nuclear fuels could have been even larger than these listed in Table 2 since they are made low by giving preference to renewables.

In 2011, the overall wind-power installed on-shore amounted to 28.7 $GW_{nameplate}$ (equivalent of 5740 wind-turbines, of 5 $MW_{nameplate}$ power each) whilst the wind-power installed off-shore, in the Alpha Ventus [8,9] and other projects, amounted to 330 MW (equivalent of 660 turbines of 5 $MW_{nameplate}$ power each) as shown in Table 2. These figures refer to the installed (nameplate) power which is available when the wind blows within an optimum velocity range and the wind-turbines are connected to the grid. When the wind is too strong the turbines are taken out of service. As shown in Tables 2, 48.3 TWh wind-electricity was generated so an average availability factor of 0.19 is applicable to the German on-shore wind-park, for the year 2011. For the off-shore park, 0.20 availability factor has been calculated which is a rather low figure since it is known that wind-energy availability for the off-shore turbines is larger than for the on-shore ones. This is attributed to commissioning problems of the new off-shore installations. If one considers the Alpha Ventus [8,9] project only, the availability factor of the 60 MW off-shore wind-park is 0.4 which is comparable with typical Danish or UK installations. In 2011, the installed nameplate power of solar-cells amounted to 25 GW which produced 19.6 TWh end-user electricity which corresponds to 2.25 GW annual-averaged power and 0.09 availability factor is applicable, as shown in Table 2. It is worth stressing that while the share of biomass in the gross electricity production was negligible in 2010 and the years before, its share increased to 5.35% within the year 2011.

[4] Gross electricity = Net electricity + Electricity used by power plants.

3. Foreseen energy demand

In the strategic study (issued in 2010) of the German Ministry for Environment (BMU), (see Fig. 5), a rapid increase in the renewables' share is projected; 18% already for 2020 and 60% for 2050. Fig. 5 underlines the point, made already in the introduction, that a very substantial increase – perhaps even an exponential one – is planned to occur in Germany as far as the share of renewables is concerned. Furthermore, the country's energy demand is projected to drop to 1950 TWh in 2050.

The German Research-Association for Renewables prepared in 2010 [4] a prognosis for the share of renewables in the gross electricity demand until 2050, which is shown in Fig. 6. The assumption for the prognosis was that by 2050, the 764 TWh end-user electricity demand would be provided up to 80% using the country's own renewables whilst the remaining 20% would be supplied by import of “green” electricity generated also from renewables in neighboring countries. The following further assumptions were made:

(a) The overall electricity demand in the industrial, transportation, residential and commercial sectors would be fully satisfied.
(b) The demand for heat would be supplied by heat pumps, solar panels, waste heat of industrial processes, combined-heat-and-power systems as well as by utilization of Synthetic Natural Gas produced during off-peak periods of electricity generation from renewables. Similarly, transportation would be based on electro-vehicles powered either by SNG or hydrogen both produced during the off-peaks periods of electricity generation from renewables or by bio-diesel.
(c) The long-term energy storage was not taken into consideration.

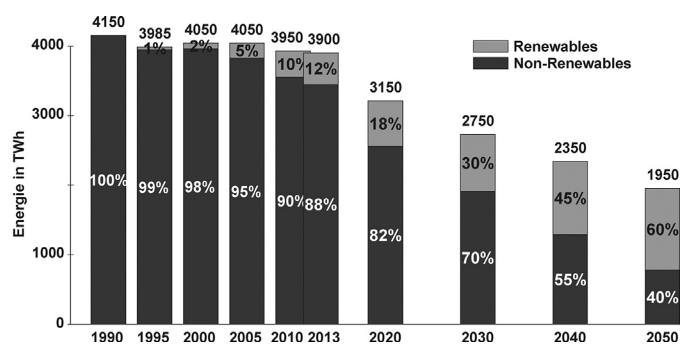


Fig. 5. Projections [4] of the German government concerning both the primary energy demand and the share of renewables.

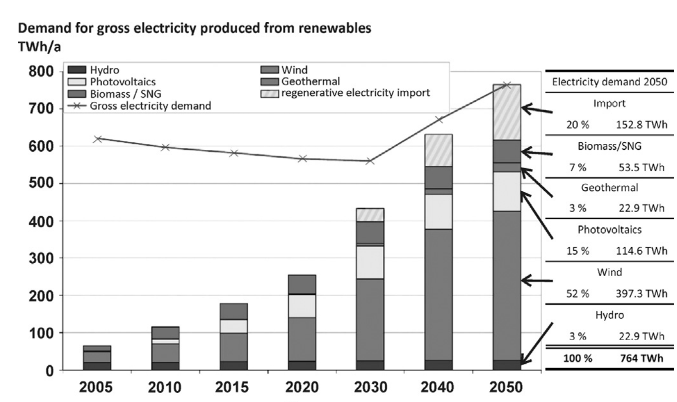


Fig. 6. Prognosis for gross electricity production using renewables (adapted from Ref. [4]).

3.1. Wind

The German Government plans to intensify the installation of wind-turbines off-shore and, by the year 2030, up to 25 $GW_{nameplate}$ wind-power is foreseen. If one takes, a 5 $MW_{nameplate}$ wind-turbine as a typical size for off-shore applications, one sees in Fig. 7 that such a turbine is equipped with a rotor of around 120 m diameter (the current Alpha-Ventus 5 $MW_{nameplate}$ turbines are equipped with a three-blade rotor of 116 m diameter, see Fig. 7) and is 148 m high. Thus, to install the extra 25 $GW_{nameplate}$ power, one needs to site 5000 wind-turbines by the year 2030; it means around 0.8 turbine per day or around 6 per week during the next sixteen years.

The prognosis of the German Research-Association for Revewables [4] assumed that 38% of the 764 TWh end-user electricity demand for 2050 (see Fig. 6), which amounts to 290 TWh, would be generated using off-shore wind-turbines (currently installed off-shore wind-park produced in 2011 around 0.33 TWh electricity, as shown in Table 2). Assuming then that (a) an average power per installed wind-turbine is 5 $MW_{nameplate}$ and (b) an availability factor of 0.4 is applicable, one can easily calculate that (on average) 83 GW wind-power is needed to satisfy the 290 TWh demand. This corresponds to around 16,600 wind-turbines of 5 $MW_{nameplate}$ power each. Until 2050, over the period of thirty-six years, 1.3 wind-turbines daily, or between eight and nine turbines weekly would have to be installed. Also here one should bear in mind that after twenty years, the existing wind-park would require a general overhaul.

3.2. Photo-voltaics (PV)

Following the prognosis of the German Research-Association for Renewables [4], (see Fig. 6), by 2050, 15% of 764 TWh end-user electricity demand (around 115 TWh) should be provided by photo-voltaics which corresponds to around 146 GW annual-averaged power, if 0.09 availability factor is retained. Thus, an increase by a factor of 5.8 is foreseen, if compared to the current (25 GW) solar-power installed. It is essential to realize that efficiencies of solar-cells have substantially increased over the last thirty years or so, see for example Refs. [10,11]. In the seventies of the last century, the efficiencies were around 2% while nowadays they typically reach 13–17% whereas currently developed cells, tested in research labs, reach up to 40% efficiencies. If the projected 2050, 115 TWh electricity demand were to be fulfilled using solar-installations of the current (0.09) availability factor, the solar-park of Germany would have to have 146 GW name plate power, which is only slightly smaller than the current electrical power of the country (175 GW). If one assumes that the availability factor increases, by 2050, by a factor of two, around 73 GW solar-power would have to be installed to produce around 115 TWh electricity.

3.3. Biomass

Biomass, in addition to wind and solar energies, is also to play a role in the future energy-mix of Germany. There are different projections regarding the biomass share. Essential arguments include considerations on agriculture and food-provision of the nation, the effect of biomass on soil-quality, required fertilization and many others. The current share of biomass in the total end-user energy demand, (see Fig. 4), amounts to 8.2%. It is foreseen (see Fig. 6) that by 2050 around 7% of the gross electricity demand, which amounts to 53.5 TWh, is going to be provided using biomass and SNG produced from biomass.

3.4. Hydro-, pumped-hydro, compressed-air and geothermal energies

Production of hydro-electricity has already reached its limits in Germany and there seem to be no sites available for further expansion. The same remark is appropriate to pumped-hydro-power for off-peak energy storage. It is clear that the share of hydro-energy is unlikely to exceed 1% in the future energy-mix of Germany (see Table 2 and Fig. 6). Nevertheless, importance of pumped-hydro and compressed-air power will increase due to their ability for both a fast storage of off-peak electricity and a fast electricity generation during the peak-demand periods. This ability is important for stabilization of the transmission grids and is not only relevant in the context of rapidly varying electricity demand but also in the context of the rapidly varying electricity production using wind-turbines and photo-voltaics.

Geothermal energy is understood here not as heat supply in residential or commercial sectors using heat-pumps but as geothermal energy available due to geothermal gradient of the Earth. Until now, the share of geothermal energy is negligible. It will certainly increase until 2050 but it is unlikely that geothermal-energy will ever become of any significance in Germany.

4. Infrastructural and technological bottlenecks

4.1. Further developments in wind-power and photo-voltaics

Nowadays, the largest wind-turbines are equipped with a 126 m diameter rotor and their peak-height is 198 m for a nominal

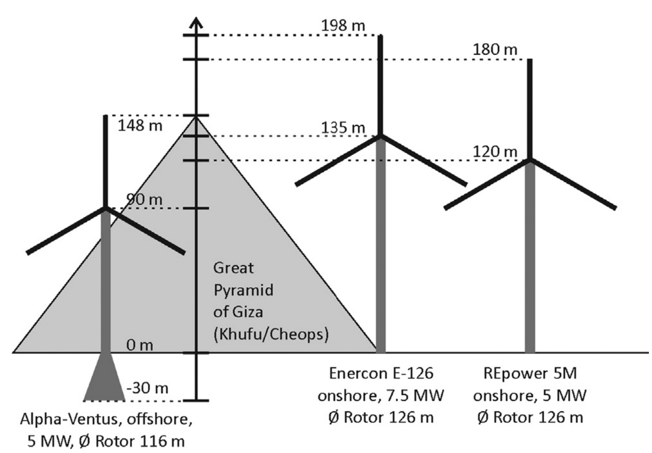


Fig. 7. Size of typical wind-turbines.

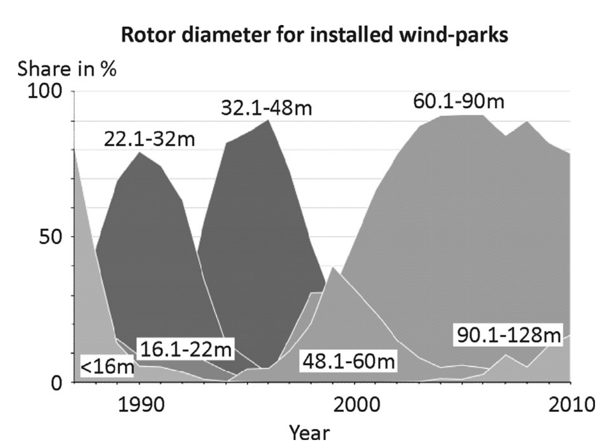


Fig. 8. Development of the rotor diameter of wind-turbines since 1987(adapted from Ref. [9]).

power of 7.5 MW, as shown in Fig. 7. Fig. 8 depicts the development in the rotor size for the last twenty-five years and further progress is to be expected [12]. From a fluid dynamics point of view alone, the distance between two neighboring turbines should be larger than around seven to eight rotor diameters. For the largest turbines the spacing should be then around 1 km since the wind power extraction is dominated by vertical entrainment of kinetic energy [13,14]. In short, challenges occur in manufacturing, installations and maintenance. There is however no doubt that the major bottlenecks are in both finding appropriate sites for off-shore wind-parks and increasing their availability factor. It can be expected that efficiency of a new generation of solar panels may be substantially increased reaching perhaps 40% in twenty or thirty years. The low availability factor (0.09) of German solar parks is determined by poor availability of solar energy and little can be done to change it.

4.2. Further developments in biomass conversion technologies

There are several ways of utilizing biomass as shown in Fig. 9. Direct combustion of biomass may provide either heat or electricity and heat (combined heat and power). Many other processes involving for example combustion, gasification, pyrolysis, and torrefaction are being currently developed to produce not only heat and electricity but also liquid and gaseous fuels for transportation (bio-diesel) or chemicals (syngas, SNG, bio-coke for ore reduction and many others).

Fig. 10 shows, as an example, a biomass gasification process to produce Synthetic Natural Gas (SNG) which is burnt in a stationary Gas-Turbine Steam-Cycle (GTSC) to produce electricity and heat. Efficiency of a typical SNG-production process is not larger than 53%, as shown in the left hand side of Fig. 10; efficiency of electricity generation in such a GTSC Power Station is typically

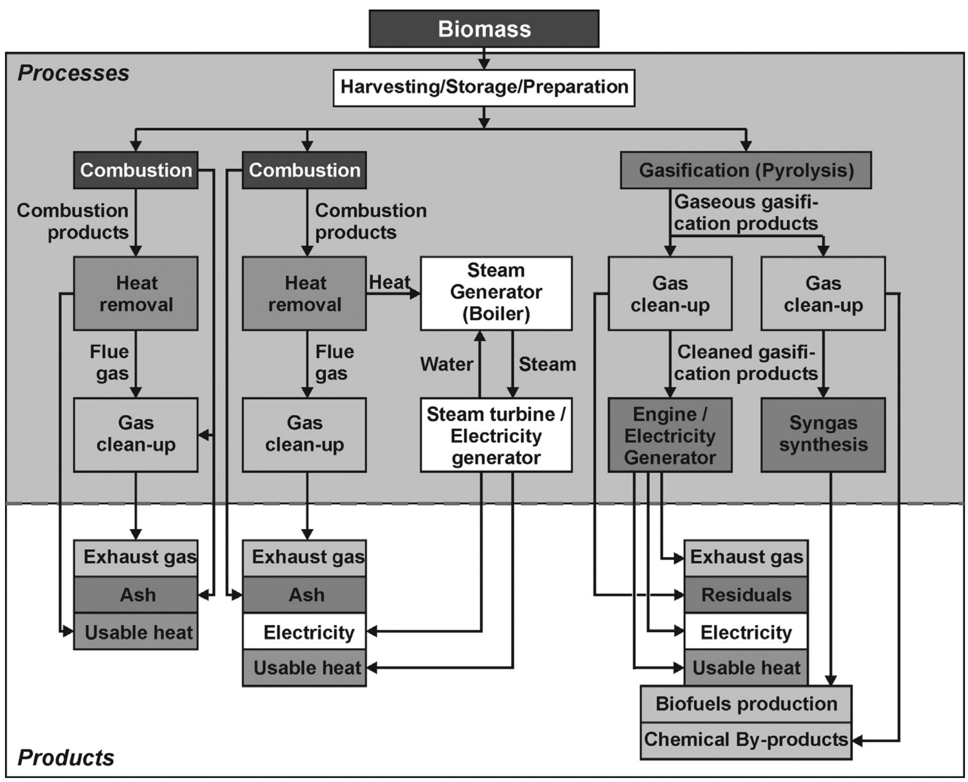


Fig. 9. Biomass conversion processes (adapted from Ref. [15]).

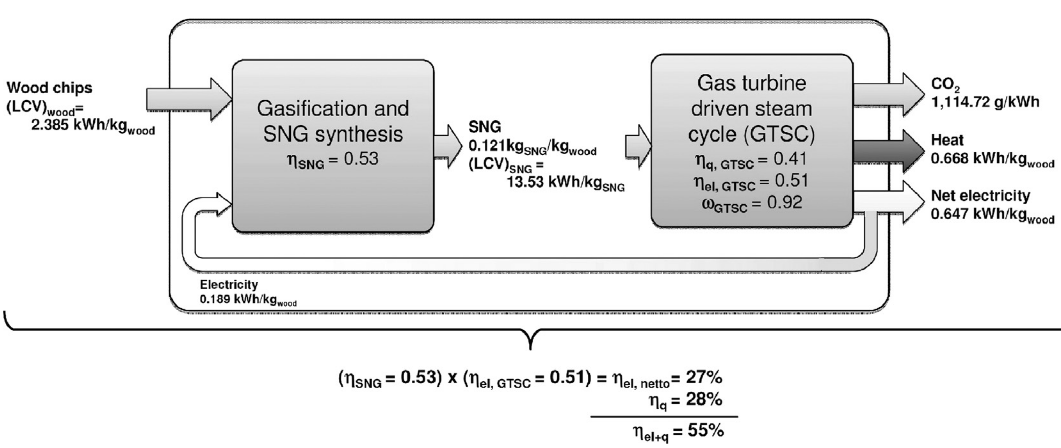


Fig. 10. Biomass–SNG–electricity and heat conversion scheme.

around 51% while efficiency of heat-generation is around 41%. Thus, the overall efficiency of the SNG conversion into electricity and heat is as large as 92%, which is an excellent figure. If one considers the overall process (gasification plus combined-heat and power), the figures of 27% and 28% for efficiencies of electricity production and heat production are applicable, respectively. Thus, the overall efficiency of the biomass to electricity and heat conversion process, is around 55%. In order to increase the efficiency of the SNG-to-electricity conversion process, one may also consider a system consisting of a solid-oxide fuel cell and an inter-cooled gas turbine (SOFC–ICGT) which may then increase the efficiency from 51% to perhaps as much as 75% [16]. However, a substantial amount of development work is still needed to achieve this, as exemplified by Refs. [17,16].

The above described process (Fig. 10) of electricity and heat production from biomass through SNG has an important advantage that the produced SNG can be stored for a long period (no SNG storage is shown in Fig. 10). The stored SNG can be used to accommodate seasonal electricity shortages due to, for example, unavailability of either solar or wind energies. When there is no demand for heat, the electricity generation from the stored-SNG has to be optimized to maximize the efficiency of the SNG-to-electricity conversion process (GTSC).

One should realize that biomass utilization processes, presented schematically in Fig. 9, are currently under development and only a few of them are commercially available. Biomass combustion in grate-fired stockers or fluidized beds for electricity production (see for example Ref. [18]) belongs certainly to the most commonly used processes although here the overall biomass-to-electricity conversion efficiency is typically not larger than 20–25% and boiler slagging and corrosion often reduce the boiler availability. One may also argue that the process of ethanol production from crops can be regarded as a mature and commercially available technology for bio-diesel production although many issues, among them the negative energy return issue, have been raised [19] and discussing them (see also [20]) is beyond the scope of this paper. As for today, there is no commercially available technology for production of SNG from biomass. The technology of synthetic methane (SNG) production from coal, through gasification and methanation [21], can be regarded as an established technology [22], although the Great Plains Synfuels Plant in North Dakota is the only plant in operation. The plant produces around five million cubic meters of SNG per day. Technologies of SNG production from biomass, through thermal- or hydro-gasification and methanation, are in the development stage. A number of pilot scale projects have been initiated as exemplified by Refs. [23–27] but, it is perhaps fair to say that the road to commercialization is long. Technologies of SNG production from biomass require further development which is likely to take decades until commercialization on a large scale is reached. The essence of the above discussion is in realizing that both wind and photo-voltaics energy technologies have been definitely more advanced and mature than biomass utilization technologies.

4.3. Electricity transmission grid

There is no doubt, wind- and solar-energies are going to provide a substantial share in the future energy conversion from renewables [4]. Thus, the development of transmission grids has been a subject of an intense discussion in Germany. According to the study (Grid II) of the German Energy Agency (DENA) [28] until 2020, around 3800 km of new high-voltage (380 kV) transmission lines are needed for the electricity transport of the 43% renewables share of the gross electricity demand (see Fig. 6). Since the appearance of the DENA study (Grid I) in 2005, only around 90 km of the new transmission lines were built until 2010. The main difficulties are in obtaining acceptance of the local communities for both new routes and expansions of existing lines. Obviously, there is a need to further develop the transmission technology through smart and flexible grids. Currently, bottlenecks exist in transmitting highly fluctuating electricity generated in wind-parks and the risk of power failures or even black-outs has risen. Not only are the high-voltage grids affected by highly-fluctuating wind-electricity supply but middle- and low-voltage grids also are often overloaded since neither the grid nor its drivers are designed for such a load variability. In short, the energy change programme invokes new challenges regarding electricity transmission grids [29,28].

4.4. Transition period from fossil fuels to renewables

In the transition period, which is likely to last for at least several decades or so, if not for a century, a coupling is needed between fossil fuel energy-conversion technologies and energy-conversion technologies based on renewable sources. Not only for the latter technologies, which are based on the renewable sources, but also for the former fossil fuel conversion processes, the energy conversion efficiencies have to be improved. This remark concerns not only fuel technologies and the relevant combustion, gasification, or pyrolysis processes but also safety issues, overall power generation process (steam generators, compressors, steam-turbines and fuel cells) as well as materials. Electricity generated in wind-parks and solar installations has to be transmitted using local and national grids and the development of smart-grids, batteries and ultra-capacitors [30–32] for stabilization of grids under rapidly varying loads must proceed further. It happens only too often that, in order to transmit “green electricity”, the conventional power stations have to be de-rated which is always associated with a loss of several points in the fuel-to-electricity conversion efficiencies. From the point of view of carbon dioxide emissions and fossil fuel consumption, the latter is highly undesirable. In short, operation of conventional coal-fired power stations under rapidly varying loads, in so called flexible load mode, is one of the most challenging issues.

In the transition period, the development of distribution grids for heat, gases (SNG) and electricity has to take place to distribute various energy carriers. Through a clever coupling of the conventional energy conversation technologies and the energy conversion technologies for renewables, one can build efficient distribution systems. Known examples include integrated industrial parks containing steel-works and chemical plants. A simple example, depicted in Fig. 11, shows co-firing of biomass with fossil fuels in conventional power stations where the fossil fuel is partially replaced by wood.[5] Although co-firing of biomass and coal in power-stations has become a mature technology, the troubling issues concern a possible loss of efficiency, operation under flexible load, fuel mixture variability, slagging and fouling as well as enhanced corrosion [33–36].

It is imperative that in the transition period from fossil fuels into renewables, technologies for conversion of wind-power into hydrogen and SNG are developed and tested. Fig. 12 shows a coupling of wind-power to drive electrolysis of water to produce hydrogen which is subsequently used to produce SNG using carbon dioxide from oxy-fuel fired power stations [37,38]. Here the idea is to utilize oxygen produced in electrolysis to oxidize fossil fuels in the oxy-fuel power plant and use the concentrated carbon dioxide to produce SNG in the methanation process [21,22]. Many other energy-smart processes can be considered: the hydrogen produced in the electrolysis can be used in steel-works to reduce iron-ores or carbon dioxide produced in the

[5] Since biomass co-firing is not subsidized by the state, only a marginal amount is co-combusted in German power-station boilers. This is in contrast to the UK, Nordic Countries, The Netherlands and Poland where state subsidies make co-firing attractive for electricity producers.

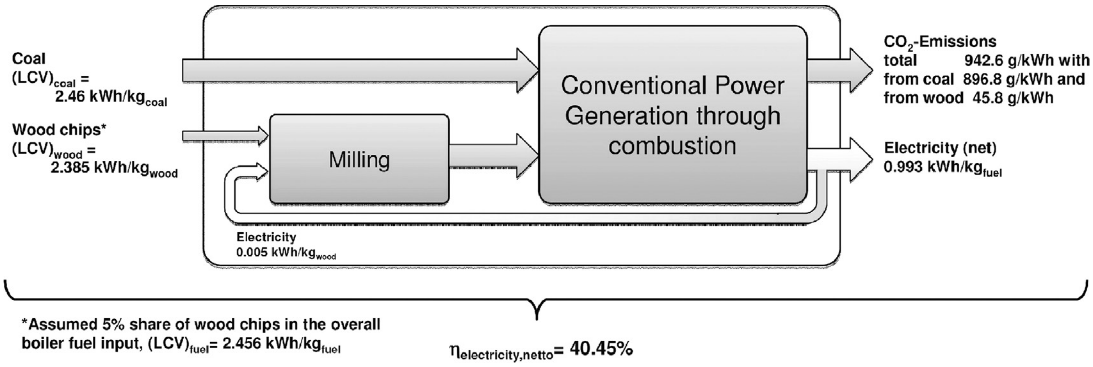


Fig. 11. Co-firing of biomass with coal.

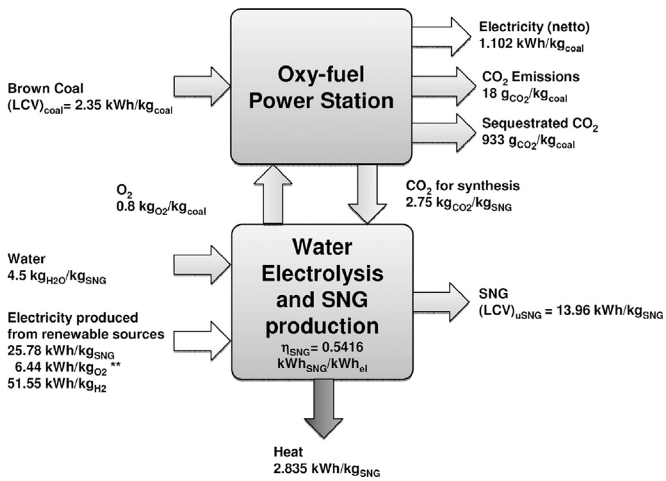


Fig. 12. Wind-energy, SNG and oxy-fuel power station coupled together.

oxy-fuel power stations can be utilized in the production of plastics. It is perhaps fair to say that relatively little effort has been allocated to the development of processes for conversion of green electricity into SNG. Here pilot scale installations are required to gather necessary experience.

4.5. Long-term energy storage

An energy system, based exclusively on renewable energy sources, which would completely eliminate fossil fuels, requires reliable long-term energy storage. Such storage is required to provide the nation with energy for longer periods of seasonal shortage of renewable forms of energy. Only substances that can store a substantial amount of chemical energy per volume are considered as good storage media. Taking into account production processes and suitability for pipeline transport, hydrogen and methane fulfil the required criteria only. Fig. 13 shows the abilities of methane and hydrogen to store chemical energy as well as the ability of water to store potential energy in an off-peak pumped-hydro-power plant. For SNG storage, a system of underground sites already exists; however, its optimized usage requires considerations on available volumes, storage depth and storage pressure. Heat transfer between the cavern's wall (rocks) and the SNG during filling up the cavern (gas compression) and during emptying (gas expansion in turbines) has to be considered due to different temperature changes occurring in compressions and expansions of the stored gas. The rate of emptying the storage site already plays an important role since a too fast rate may result in a too excessive a drop of gas temperature which may temporarily reduce the site's storage capacity. When the stored fuel gas is slowly heated by the caverns' rocks, the storage capacity is restored. Such effects, leading to a loss of energy stored, have been neglected in the estimates shown in Fig. 13. The energy density of water in off-peak hydro-power plants is also shown in Fig. 13 to facilitate comparison. If one takes, as an example, a pumped hydro-station operating at a 100 m elevation differential, at around 1000 times larger storage volume is needed, if compared to hydrogen or methane sites.

4.6. Conversion of wind and solar energies into SNG

In Fig. 14, a conceptual scheme of a power-station is shown where water electrolysis, SNG production through methanation [21,22], and SNG combustion with oxygen are coupled into a unit which allows for continuous electricity and SNG production as well as for SNG storage and usage. Wind and solar energies are the primary energy forms which are converted into electricity, SNG and heat. The individual technological building blocks, namely electrolysis, methanation, and oxy-SNG combustion, are already established processes. Hydrogen is produced first using electricity generated in wind- and solar-parks (see reaction (1) in Fig. 14). Hydrogen is subsequently converted into SNG in methanation reactions (reactions (2) and (3) in Fig. 14). Both electrolysis and methanation are in principle established technologies and, in the concept shown in Fig. 14, one expects around 50% efficiency of the wind-energy to SNG conversion process. It is likely, that this 50% efficiency can be improved by optimizing the heat management of the process since the water electrolysis is endothermic while methanation is exothermic. The efficiency (η_{SNG}) is here defined as the ratio of the SNG enthalpy to the amount of electricity generated in the wind- or solar-parks. With $\eta_{SNG}=0.5$, the conversion factor[6] (A), applicable to the conversion of the electricity generated in wind- and solar-installations into SNG chemical enthalpy is

$$A_{green\_electricity \rightarrow SNG\_enthalpy} \cong \frac{E_{green\_electricity}}{E_{SNG\_chemical\_enthalpy}} = 2$$

where $E_{green\_electricity}$ stands for the amount of electricity produced in wind- and solar-parks and used for the SNG conversion whilst $E_{SNG\_chemical\_enthalpy}$ is the chemical enthalpy of the SNG produced. The produced SNG can be stored and losses occurring by charging and emptying the SNG storage site have been neglected. If there is then demand for electricity, the stored SNG can be combusted with oxygen in an oxygen-blown GTSC (see reaction (4) in Fig. 14) for which $\eta_{GTSC}=0.6$ conversion efficiency is applicable. Thus, the

[6] The energy conversion factor (A) is introduced since it is often used in evaluation of energy conversion processes. In this paper A is a simple reciprocal of the overall conversion efficiency η.

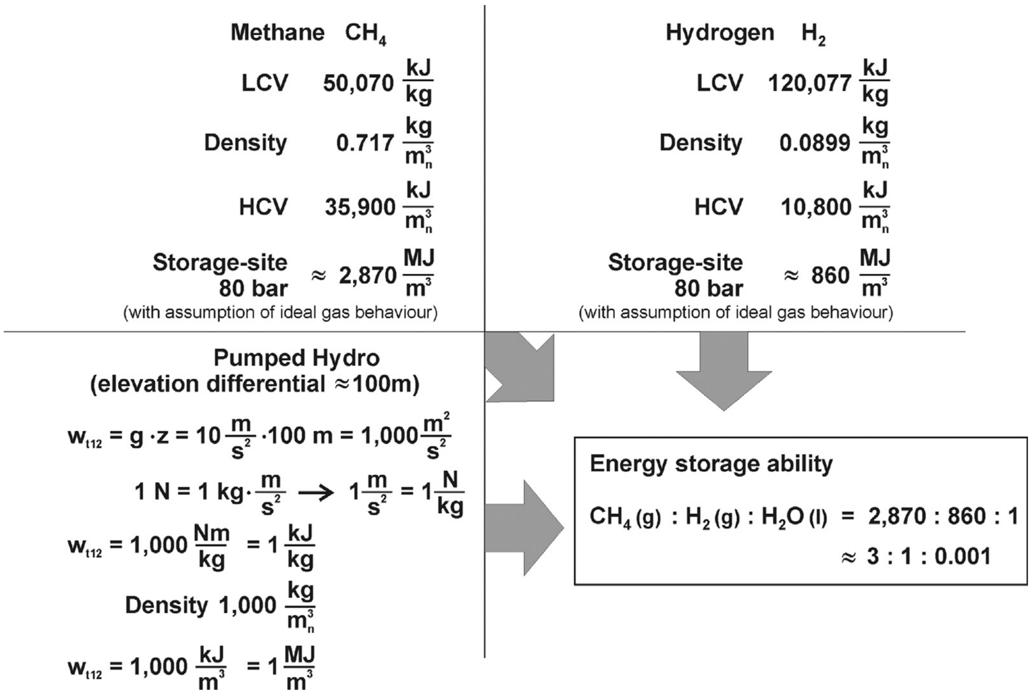


Fig. 13. Energy storage density of methane (SNG), hydrogen and water.

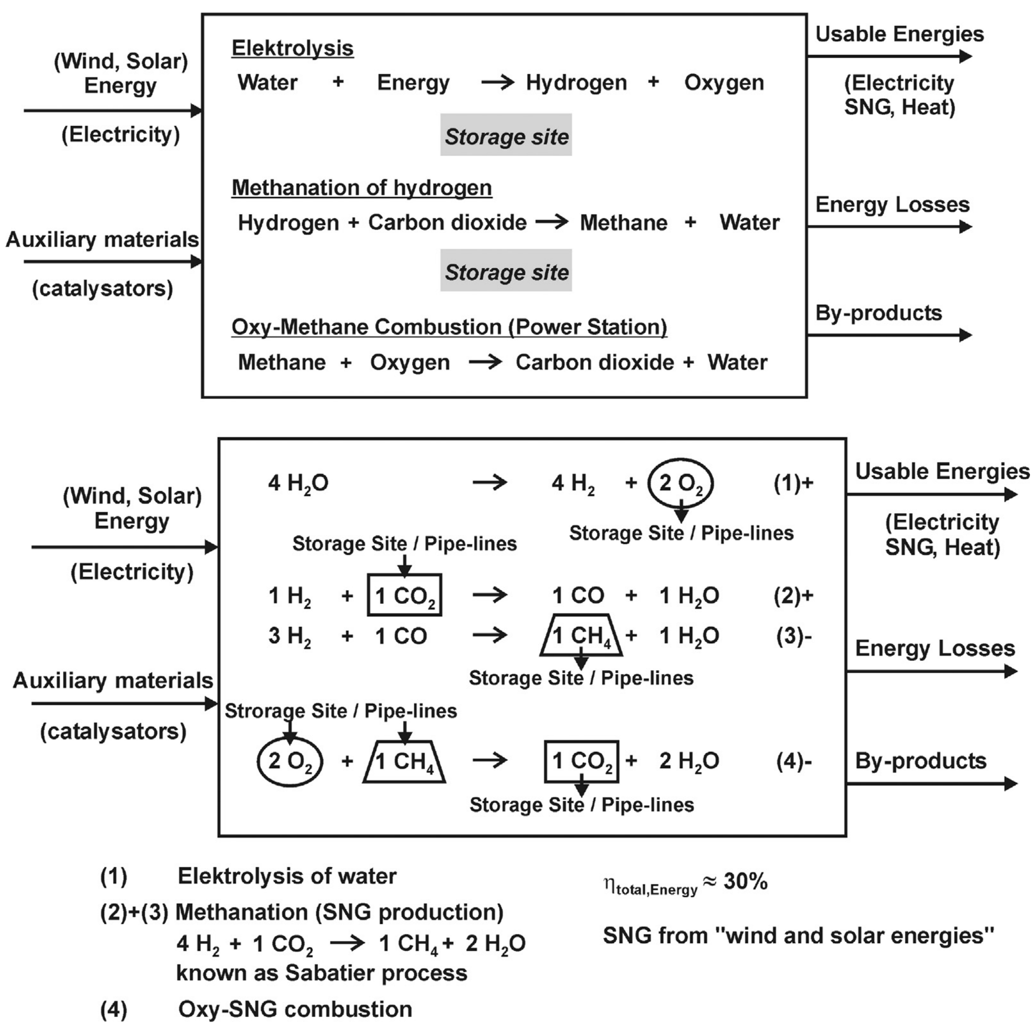


Fig. 14. Conversion of wind and solar energies into electricity, SNG and heat in a power station.

overall conversion efficiency is

$$\eta_{green\_electricity \to storred \to end-user\_green\_electricity} = \eta_{SNG}\eta_{GTSC} = 0.5 \times 0.6 = 0.3$$

or, in other words, the conversion factor (A) is

$$A_{green\_electricity \to storred \to end-user\_green\_-electricity} = \frac{E_{green\_electricity}}{E_{end-user\_green\_electricity}} = \frac{1}{0.3} = 3.3$$

In summary, energy "picked up" by rotors of wind-parks is converted into electricity with efficiency close to 1. In a completely self-sufficient[7] economy, based exclusively on renewable forms of energy, around 30% efficiency of the conversion process: green-electricity → SNG storage → end-user-green-electricity is applicable. We recall that nowadays in Germany the average efficiency of all currently used processes for energy conversion into electricity is around 38% which corresponds to the energy conversion factor (A) of

$$A_{primary\_energy\_mix} = \frac{E_{primary\_energy\_mix}}{E_{end-user\_electricity}} = \frac{1}{0.38} = 2.6$$

For the sake of completeness, we recall (see Section 4.2) that the overall efficiency of the biomass-to-electricity conversion process shown in Fig. 10 is around 0.27, so that the energy conversion factor (A) in this case is

$$A_{biomass \to end-user\_green\_electricity} = \frac{E_{primary,biomass}}{E_{end-user\_green\_electricity}} = \frac{1}{0.27} = 3.7$$

Certainly, combustion (reaction (4) in Fig. 14) can be carried out in air as an oxidizer. However it is meaningful (see Fig. 14) to use oxygen (produced in the water electrolysis) in re-converting SNG-stored energy into electricity. This would require the development of an oxygen-blown GTSC which is certainly feasible. Following Fig. 14, oxygen produced in the electrolysis should also be stored so as to make the re-conversion of SNG into electricity independent from the electrolysis. The usage of oxygen in the SNG combustion process has an advantage that the carbon dioxide can be used in methanation so that CO_2 emissions to atmosphere can be minimized. Since energy supply often cannot be synchronized with its demand, storage for carbon dioxide has to be provided. In the above underlined concept (Fig. 14), hydrogen, oxygen, carbon dioxide, methane, carbon monoxide and water vapor remain in a close-loop circulation only when re-conversion of the SNG-stored energy into electricity proceeds under steady-state operation. In the case when only SNG-stored energy is being converted into electricity and the other processes (reactions (1)–(3) in Fig. 14) do not proceed, a shortage of hydrogen occurs which then should be covered by an extra supply from a storage site. In addition to electricity and SNG, usable heat is also produced which should be used to increase the overall process efficiency.

To emphasize, the primary reasons for a fully self-sufficient[8] system for energy storage presented in Fig. 14 are as follows:

(a) To propose a concept of a SNG storage system for provision of electricity and chemical energy during long-term (up to three month period) shortages in renewables. During re-conversion of the SNG-stored energy into electricity, which is needed not only during periods of peak-demands for electricity but also for stabilization of the transmission grids, the oxy-SNG-combustion (oxygen blown GTSC) is advantages since the produced CO_2 can be used for hydrogen methanation.
(b) In economy, which is based exclusively on renewable energy sources, the industry is provided with fuels, or in other words with chemical energy, to carry out high temperature processes of glass, iron, steel and cement manufacturing. These industries would have to undertake a process of readjustment to the new energy carriers which due to similarity between SNG and natural gas should not be a problem. In many documents [4,5] which are concerned with Energiewende policy, provision of the industries with regenerative forms of energy has hardly been considered.
(c) One should consider every application individually in order to determine whether the re-conversion of the SNG-stored energy into electricity (GTSC) is absolutely necessary since the overall efficiency of the process is not larger than 30% (see above). For example, it would be more meaningful to drive a significant portion of transportation vehicles using SNG directly rather then driving E-vehicles charged using electricity produced during the re-conversion process. Obviously, in addition to the directly SNG powered transport vehicles, one may consider conversion of part of the SNG into electricity within the vehicle (hybrid-vehicles).

4.7. Summary of technological developments needed

The planned (complete) replacement of the fossil fuels energy conversion processes with renewable energy forms is a project of overwhelming scope and complexity. In the above discussion we have identified the areas where further developments are needed. Below we list these areas explicitly as follows:

(a) further development of technologies for conversion of renewables,
  wind-energy into electricity and SNG,
  solar-energy into electricity and SNG (solar panels and solar power plants), and
  biomass into gaseous and liquid fuels, SNG, electricity and heat,
(b) development and expansion of the electricity transmission grid,
(c) development and installation of heat pumps,
(d) further development of water electrolysis process,
(e) further development of methanation process,
(f) development of systems for long-term storage of electricity through chemical energy,
(g) development of electrical energy storage system based on batteries and ultra-capacitors,
(h) further development of the gas pipe-lines (later on to be fed with SNG),
(i) further development of the gas-storage sites (later on to be fed with SNG),
(j) further development of
  conventional gas-fired power stations,
  fuel cells technology,
  biomass processing including combustion, gasification, pyrolysis,
  production of gaseous and liquids bio-fuels,
  processes for utilization of secondary-fuels and wastes, and
  processes for utilization of low-BTU industrial gases,
(k) further development of combined heat and power, and
(l) further development of grids for short and long distance transport of heat.

In the transition period, during which the fossil fuels energy conversion processes are gradually being replaced by renewable energy forms, conventional power-stations have to readjust their operation to the new situation. Of particular importance is the

[7] Self-sufficient here means without any fossil fuels support.

need to react quickly to variable loads and natural gas fired electricity generators are to play an important role to stabilize the national energy system. One should bear in mind that these natural-gas fired electricity generators (relatively simple units) are to be finally replaced by SNG fired turbines coupled into a complex energy system network. Giving preference to renewable energy forms invokes a decrease in the fuel conversion efficiency of conventional coal-fired power stations which, in the context of CO_2 emissions and conservation of energy reassures, is highly undesirable. Problems associated with variable fuel quality, as well as the blending of coals with biomass are not to be underestimated since they often lead to a decreased availability of conventional power stations due to enhanced slagging/fouling and corrosion. As can be clearly seen, the transition period is likely to last for a century rather than for several decades.

5. Estimating German end-user energy demand assuming the country uses exclusively renewable energy sources

In 2012, the end-user energy demand for Germany amounted to 2499 TWh (9.06 EJ) [3], (as shown in Fig. 3), and this amount did not include any energy-reserves. The German laws concerning national energy economy [39] require that 25% (corresponding approximately to the three month end-user energy demand) of the annual energy demand has to be stored, as natural gas in underground storage sites and as crude oil in tanks, as a national security measure.

If one follows the projections [4] shown in Fig. 6, for 2050, the country will need around 764 TWh (2.75 EJ) gross end-user electricity of which 52% (397.3 TWh) is projected to be produced by wind-parks. In the 764 TWh (2.75 EJ) forecast, the electricity for transportation (electro-mobility) is included. Also included is the electrical energy needed to drive heat-pump systems to be installed throughout the country to produce 500 TWh thermal energy [4] for heat usable in households, commerce and industry. Additionally, one has to consider the non-electrical energy demand for industry. Assuming that the demand for chemical energy in form of syngas, SNG, and hydrogen remains at the level of 19.8%, as for the year 2012 (see Fig. 3), one obtains the amount of 495 $TWh_{chemical}$ for the end-user chemical-energy demand. Then, the total end-user energy demand for electrical, thermal and chemical energies is estimated to be $764+495+500=1759$ TWh. Thus, it is foreseen that the current (year 2012) 2499 TWh demand is going to be reduced in the year 2050 to 1759 TWh which seems to be a rather optimistic projection.

To produce (in year 2050) the projected 397.3 TWh (1.43 EJ) electricity, 22,677 off-shore wind-turbines of 5 $MW_{nameplate}$ power are needed, if the availability factor is at the 0.4 level. We assume that 52% (see Fig. 6) of the 495 TWh end-user chemical energy demand is going to be provided by wind. To satisfy the ($495\ TWh \times 0.52$)= 257.4 $TWh_{chemical}$ demand, with around 50% efficiency (see Fig. 12 where 54% conversion efficiency is shown) of wind-electricity into chemical-energy (SNG) conversion process, one needs a primary wind-energy supply of 514.8 $TWh_{electrical}$. Assuming again that wind-turbines of 5 $MW_{nameplate}$ are used with 0.4 availability factor, one needs 29,384 wind-turbines to satisfy the 257.4 $TWh_{chemical}$ demand. Thus, $(22{,}677+29{,}384)=52{,}061$ wind turbines of 5 $MW_{nameplate}$ power have to be in operation by 2050. Furthermore, 237.6 TWh chemical energy is going to be converted using other than wind forms of renewables and 500 TWh is foreseen for thermal energy. Table 3 summarizes the above calculations. We emphasize that the estimate does not include the three-months of energy storage required for national security.

In the above estimate we assumed that 52% (see Fig. 6) of 495 $TWh_{chemical}$ demand would be provided by wind, and that the technology for conversion of the wind-energy into SNG exists. Both assumptions deserve comments. While seeking technological options for producing 495 $TWh_{chemical}$ energy, as SNG or other gaseous fuels, also biomass and solar-energy are coming into considerations. It is arguable whether their share will be as large as 48% since biomass conversion requires both huge amounts of biomass and substantial development work (see Section 4.4) to become applicable on such a wide scale whilst conversion of solar-energy into gaseous fuels is in the research phase. Furthermore, technologies of SNG production using wind-energy do require substantial development work as pointed out in Section 4.6. Thus, the above estimated number (29,384) of wind turbines is likely to be an underestimate.

As for today, wind-energy-technology is the most mature among the renewables. It is therefore worth considering what happens when the country's (projected for 20,150) 1759 TWh (6.34 EJ) energy demand is provided by thermal energies (heat pumps), up to 500 TWh amount, and by wind up to 1259 TWh (764 TWh (electricity)+495 TWh (chemical)). To fulfil 764 TWh requirement for electricity, 43,607 wind-turbines of 5 $MW_{nameplate}$ power are needed whilst for provision 495 TWh of chemical energy another 56,507 turbines are required. This makes in total a wind-park of 100,114 turbines, each of 5 $MW_{nameplate}$ power. Such a scenario has been considered in our previous publications [41-43] where a figure of around 100,000 wind turbines was quoted.

Now we consider a SNG energy storage system which would allow for storing 25% of the country's end-user annual energy demand. Such a system has to be large enough to store $0.25 \times 1759\ TWh = 440$ TWh with the following split: 191 TWh electrical-, 125 TWh thermal- and 124 TWh chemical-energy. We assume here that the system would have to be completely refilled with SNG once every two years using wind energy. As shown in Fig. 15, to provide a back up for 191 TWh electricity, one has to store 382 TWh of SNG which would require 21,804 wind-turbines of 5 $MW_{nameplate}$ power. If one assumes (optimistically) that the demand for the stored electrical and thermal energies occurs simultaneously, one can produce thermal energy in a combined heat and power system, as shown in Fig. 15, in the amount of up to 152 TWh which is larger than the required 125 TWh for thermal energy back up. For storage of 124 TWh chemical energy, a wind-park of 7077 turbines is needed. Thus, up to $(21{,}804+7077)=28{,}881$ wind turbines might be required to produce the SNG for the three-months energy back up. Other renewables may also be used for refilling the SNG system and one may argue that the estimated number (28,881) of wind turbines is too large.

Table 3
Estimate of the end-user energy demand for Germany assuming the country uses exclusively renewable energy sources (three months energy storage needed for national security has been neglected in this estimate).

End-user energy demand		Number of 5 $MW_{nameplate}$ wind-turbines required
Electrical energy [4] (see Fig. 9)	**764 TWh**	
52% from wind (397.3 TWh)		22,677
20% import (152.8 TWh)		–
29% other renewables (213.9 TWh)		–
Thermal energy [4]	**500 TWh**	–
Chemical energy *	**495 TWh**	
52% from wind (257.4 TWh)		29,384
48% other renewables (237.6 TWh)		–
Total	**1759 TWh**	52,061

* 19.8% of 2499 TWh (see Fig. 3). The 52%/48% split is based on Fig. 6.

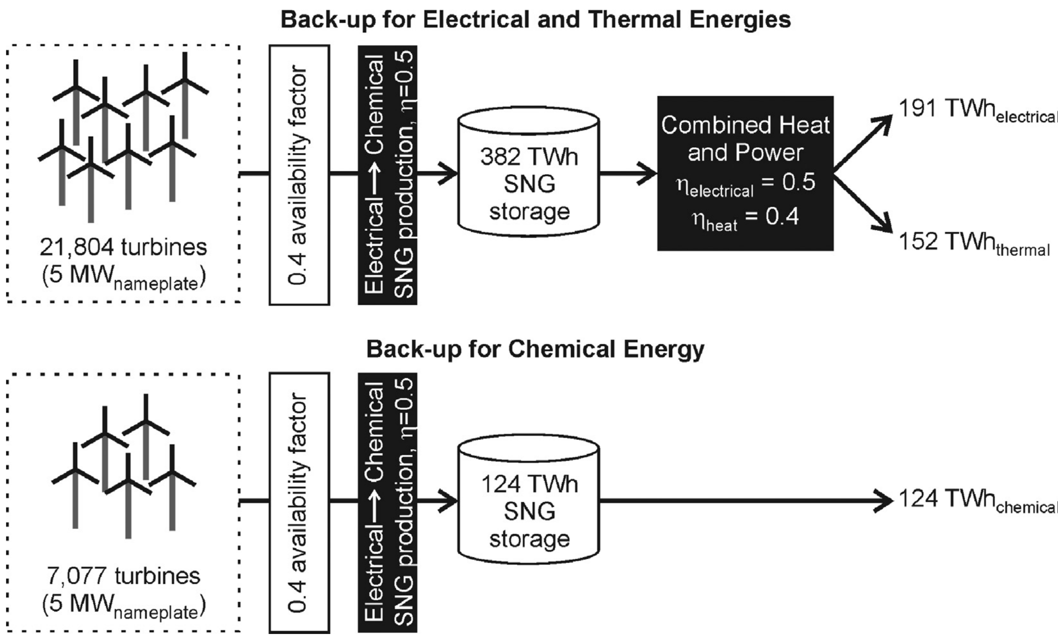


Fig. 15. SNG based storage system for providing three months of energy back up in Germany.

Referring to Fig. 6, we recall that for the year 2050 the end-user energy demand of 764 $TWh_{electrical}$ + 495 $TWh_{chemical}$ = 1259 $TWh_{electrical+chemical}$ is foreseen. Thus, the storage must contain

– for three-month reserves of 0.25 × 764 $TWh_{electrical}$ = 191 $TWh_{electrical}$ energy, with an efficiency of 0.5 applicable to GTSC systems, one needs to store around 382 $TWh_{chemical}$ energy, and
– for three-month reserves of 0.25 × 495 $TWh_{chemical}$ = 124 $TWh_{chemical}$ energy, one needs 124 $TWh_{chemical}$ in the storage (no energy loss on discharge of the storage site).

Thus, Germany needs the storage capacity of around 506 $TWh_{chemical}$ for the planned 2050 energy system. Since the lower calorific value (LCV) of SNG is around 36 MJ/m_n^3 (standard conditions), a 50×10^9 m^3 storage volume is needed. Nowadays, Germany has a storage volume of around 20×10^9 m^3 [42] in around fifty currently used sites. Since the existing sites are also suitable for SNG storage almost half of the storage volume is already available.

The above considerations are not to calculate exactly the number of wind-turbines needed but to indicate the enormous scale and complexity of such a national system based exclusively on renewables. The occurrence of numerous constraints and bottlenecks is obvious. The enormous scale of the "only green energy" venture can be comprehended by realizing that around 52,000 wind-turbines (5 $MW_{nameplate}$ average power) are going to be needed to meet the every-day energy demand of the country. For the three months energy storage system perhaps as many as 30,000 turbines would have to be in operation. We recall, that currently installed wind-power in Germany amounts to 29 GW which corresponds to 5800 wind-turbines of 5 $MW_{nameplate}$ power.

6. Exclusively Green Energy Communities (EGECs)

In order to determine whether Germany can function as an economy and as a society using exclusively renewable energy sources, it is desirable to initiate demonstration projects to verify not only the feasibility of the concept but also to determine whether modifications are needed, or perhaps the timetable requires alteration. Certainly, one can develop a number of concepts for such demo projects. One option is to select demo-communities, which should include residential and commercial sectors and industry, so as to represent a typical German-mix. Life within such communities, which we here name as Exclusively Green Energy Communities (EGECs), should be organized so as to function using energy which is produced exclusively from renewables. The assumption is that the EGECs should function even when the supply of wind or/and solar energy, or more generally renewables, is intermitted or stopped for periods up to three months. During these intermittency or long-term shortage periods, no support of fossil fuels energy should be allowed. It is worth stressing that the proposed EGECs differ substantially from existing Green-Energy-Communities in Germany. The later are communities, typically small villages, where electricity is generated using either nearby standing windmills and/or biogas installations. In large cities, some street-cars are powered by electricity generated using renewables and this alone is called a Green-Energy-Community.

Fig. 16 shows a concept for such an EGEC where wind is the only renewable. The energy system shown in Fig. 16 is to serve a community of around 3400 inhabitants living on an area of around 15 km^2. Such a GEC would represent around 0.0041% of the nation area as well as population. In terms of energy, using the year 2011/2012 data (Fig. 1), such an EGEC would need around 105 GWh (0.38 PJ) of end-user energy, it means 12 MW power must be available on average with around four-fifth in form of electricity (9.6 $MW_{electrical}$) and one-fifth as chemical energy (2.4 $MW_{chemical}$) through SNG.[8] Using (optimistically) 0.4 availability factor for the electricity produced using wind turbines, five (9.6 $MW_{electrical}$/0.4/5 $MW_{nameplate}$ = 4.8) wind-turbines of 5 $MW_{nameplate}$ power are needed. To supply the 2.4 $MW_{chemical}$ power using SNG, for which 0.5 conversion efficiency is applicable, one needs another three (exactly 2.4) 5 $MW_{nameplate}$ turbines. Thus, eight wind-turbines are required.

In the calculations that follow, we assume that the capacity of the long-term energy storage of the EGEC should be large enough

[8] The split 1/5 chemical and 4/5 electrical, corresponds to the 2012 data shown in the table in Fig. 3.

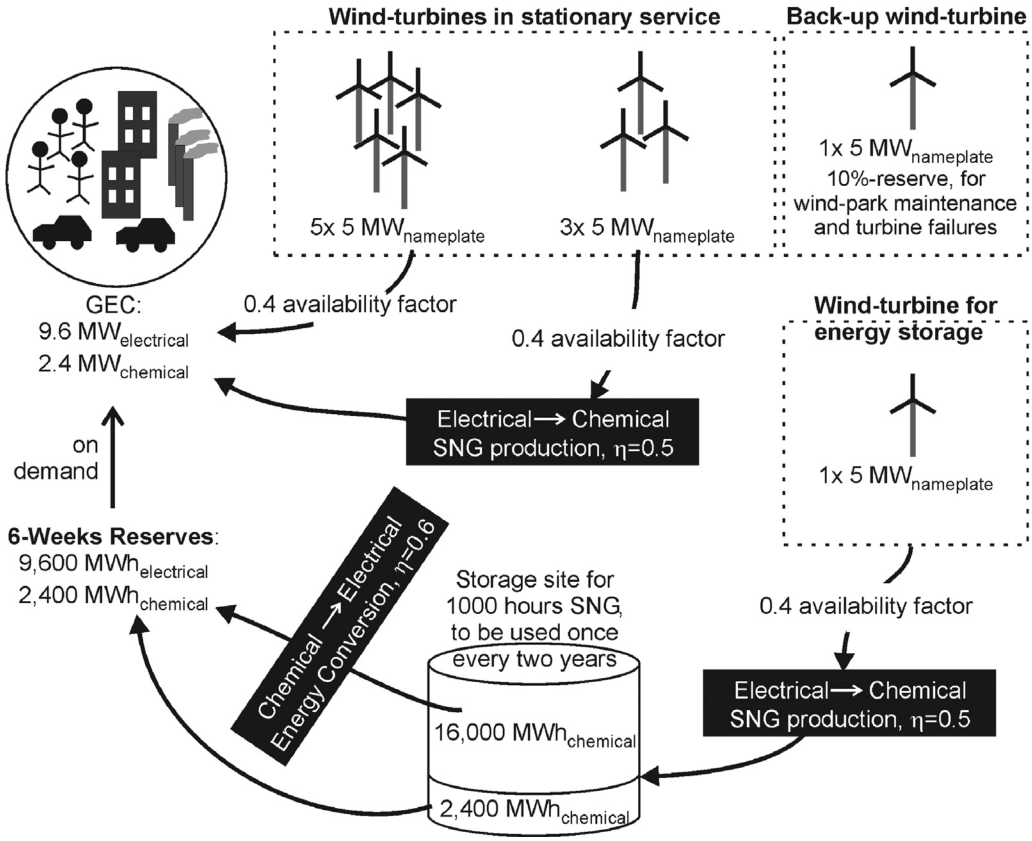


Fig. 16. Exclusively Green Energy Community (EGEC) concept.

to secure 1000 h (around 6 weeks) energy reserves. Thus, for 2.4 $MW_{chemical}$ power over a period of 1000 h the amount of 2400 $MWh_{chemical}$ must be stored. For 9.6 $MW_{electrical}$ power, over the same period of 1000 h, the amount of 9600 MWh must be available by conversion of SNG energy into electricity which proceeds with efficiency of 0.6 ($MWh_{electric}/MWh_{chemical}$) so that the amount of 96,000 $MW_{electrical}/0.6 = 16{,}000$ $MWh_{chemical}$ must be stored as SNG. Altogether, the SNG storage-capacity amounts to 18,400 $MWh_{chemical}$ which must be produced, with 0.5 conversion efficiency, by the wind-park. Therefore, the amount of 36,800 $MWh_{electricity\_from\_wind}$ is then needed. Assuming then that every two years the storage-capacity of 36,800 $MWh_{electricity\_from\_wind}$ is emptied and must be restored over a period of two years (17,520 h), the power of 2.1 $MW_{electrical}$ is needed; using wind-turbines operated with availability factor of 0.4 an another wind-turbine of 2.1 $MW_{electrical}/0.4 = 5.25$ $MW_{nameplate}$ power is then required. Thus, nine 5 $MW_{nameplate}$ wind-turbines are needed. If one then takes a 10% safety margin, it means a spare turbine is needed to be used during maintenance of the wind-park, one ends up with ten wind-turbines for the EGEC considered, as shown in Fig. 16.

The above estimate is based on the assumption that the 12 MW end-user power of the EGEC is being split[8] into four-fifth as electricity and one-fifth as chemical (through SNG). If one takes the split – two-thirds as electricity and one-third as chemical (SNG)- the calculations (see Refs. [40,41,42]) show that also ten 5 $MW_{nameplate}$ wind-turbines are needed. Thus, the proposed energy system can function also when the demand for chemical energy reaches 30% of the total amount.

On the basis of the above considerations, one can easily estimate the capacity of the SNG-storage site. Since the energy stored as SNG amounts to 18,400 $MWh_{chemical}$ and the LCV of SNG is around 36 MJ/m_n^3, the storage volume 1.84×10^6 m_n^3 is needed which for a storage pressure of 80 bar corresponds to 21,500 m^3 storage-volume (ideal gas). Since emptying such a tank completely is undesirable, it should operate at 60 ± 20 bar and therefore its capacity should be around 43,000–46,000 m^3 which for a cubical tank shape corresponds to 35 m × 35 m × 35 m cube.

To provide a smooth supply of electricity in the considered EGEC, the grid system which transmits electricity from the wind-park to the end-users, will have to be equipped with an electricity storage system (not shown in Fig. 16), based on batteries and ultra-capacitors, in order to compensate for temporary variations in the wind strength and availability. If one then assumes that such a system should be large enough to provide the EGEC's electricity when a 2 h shortage of wind-energy occurs, then its minimum capacity should be (12 MW × 2) = 24 MWh. Since the depth of discharge should not be larger than approximately 15% and an efficiency of battery modules is typically in the range 60–80%, the capacity of such a system should be around (24 MWh/0.15/0.8) = 200 MWh. This will allow for delivering 12 MW power for a period of around 20–30 min after which the power will gradually decrease. During this twenty to thirty minute period, an SNG-driven gas turbine would have to be brought in operation to stabilize the energy supply. The reader will notice that the 12 MW battery storage may not be large enough for shifting night time electricity production to day time when the peak power is needed and, in practice, more batteries may be needed and a storage of 24 MW is likely to be required. Flow batteries and sodium-sulphur batteries (NaS) belong to the most advanced electricity storage technologies and nowadays they are under development and testing at the tens of megawatts scale. The World's largest electricity storage system coupled with a wind-park is being installed at the Japan Wind Development Co. Ltd. (Rokkasho village, Aomoni Prefecture). The system contains 34 MW NaS batteries (17 × 2 MW stacks) which provide the storage for the 51 MW wind-park. On

average fifty to sixty charge-recharge cycles are performed per hour. The above paragraph underlines the complexity of energy storage "at the grid-scale" and no considerations to the reliability, durability and costs of such storage systems have been given. It is perhaps fair to say that decades of further development are needed to developed cheap and long-lasting systems based on batteries which could be widely applied. On the basis of the above considerations it is also clear that, as for today, electrical batteries do not provide a viable option for long-term energy storage even for the considered (small) EGEC. Instead, their role is in "firming" the electricity supply of the wind-farms.

One should realize that for an operation of the EGEC, in addition to the ten 5 $MW_{nameplate}$ wind-turbines, the batteries/capacitors and the electricity transmission grid, the SNG storage place and the gas pipe-lines, the following components are needed: (a) a plant for water hydrolysis and methanation of hydrogen, (b) oxygen storage-tank and pipe-lines, (c) carbon dioxide storage tank and pipe-lines, (d) oxygen blown GTSC plant, and (e) an intelligent control system. The electricity demand for operating such an energy system is likely to be negligible, if compared with the above estimated energy amounts.

By operating such a EGEC for a longer period, one would gain essential experience concerning (a) flexibility in coping with peak-energy demands, (b) functionality in periods of long-term shortages of wind and solar energies, (c) the energy infrastructure (electrical grid, pipe-lines, and storage-places) of the system, and (d) control and optimal usage of the energy resources.

7. Technical arguments often misused in current Energiewende debates

7.1. Wind-energy

In the on-going debates on Energiewende, it has often been argued that full substitution of fossil fuels with wind energy alone in the electricity generation sector is sufficient to decrease the primary energy demand to a level which is close to the end-user energy demand since the energy "picked up" by rotors of wind-turbines is converted into electricity with an efficiency close to 100% and therefore the 38–40% losses, applicable to fossil fuel conversion, do not occur. This argument is incorrect. Even if the electricity were to be produced exclusively from renewables (wind-turbines, photo-voltaics or biomass), the energy would have to be stored, perhaps even up to three months or longer. Until now, the only feasible option for long-term storage of large amounts of energy is through energy conversion into chemical bonds by producing either methane (named often as Synthetic Natural Gas – SNG) or hydrogen. Such gaseous fuels are however produced with an energy conversion efficiency in the 53%–60% range (see Section 4.6) and by re-converting their chemical energy back into electricity, when there is need to use the stored energy, an efficiency of 50–60% is applicable. Thus, the overall efficiency for storage of the wind-energy (conversion into SNG and re-conversion back into electricity) is in the range 26.5–36%.

7.2. Energy-storage in batteries

Of course wind and solar energies can be stored in batteries and/or ultra-capacitors. Batteries have been used for decades in distributed power systems and have high energy storage density but lower power density, if compared to ultra-capacitors. It is unlikely that batteries or ultra-capacitors are going to be capable of storing large amounts of energy for several weeks or months in the foreseeable future. They are however going to play an important role [30,31,43] in stabilising the local grids and in firming the electrical current (see Section 6).

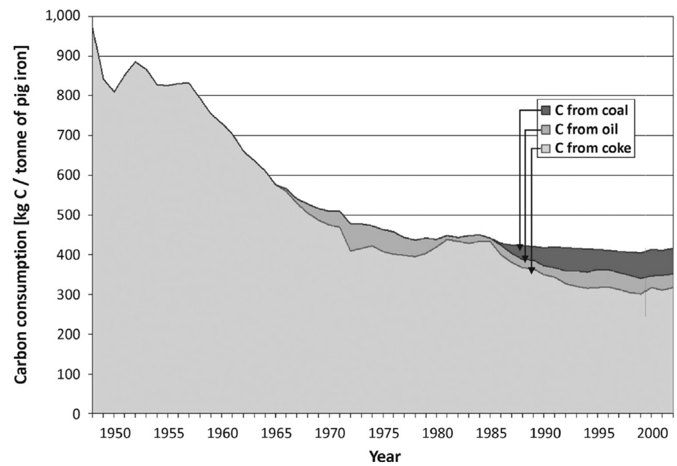


Fig. 17. Development of energy consumption in iron-ore reduction process (blast furnace) over the last two decades (adapted from VDEh Hochofenausschuβ – Steel Institute; Blast Furnace Working Group).

7.3. Energy-conversion efficiencies in the industry

In German industry, possibilities for increasing energy conversion efficiency and subsequent reduction of the end-user energy demand exist; however they are limited. In energy intensive industries (chemical, iron and steel, non-ferric metals, cement, glass, ceramics and others) many processes have already been optimized and the current energy demand is close to the minimum which is determined by the physics/chemistry of the processes in question. In industrial processes, which from an energy stand point have already been optimized, the energy demand cannot be decreased any further. To illustrate the point, Fig. 17 shows the energy demand for production of pig iron in blast furnaces; the demand has been decreased by a factor of two over the sixty years or so and for the last twenty years it remains approximately constant approaching the minimum value asymptotically. In such cases, completely new technological processes have to be developed to decrease the energy demand further. It is easy to formulate such a requirement; however its implementation requires new technological processes whose development time scale is difficult to project.

8. Concluding remarks

Both current and foreseen energy demands in the context of the Energiewende (energy switch/change policy) in Germany have been considered. The paper has underlined the enormous scale of the Energiewende and has identified numerous infrastructural and technological bottlenecks. We have estimated (perhaps a bit optimistically) that the country may require only 1759 TWh end-user energy in 2050 if its energy demand is to be provided exclusively by renewable sources. In the 1759 TWh projection, which constitutes around 70% of the 2012 end-used demand (2499 TWh), the following split is foreseen: 764 TWh electrical-, 495 TWh chemical- and 500 TWh thermal-energy. The estimate includes the residential and commercial sectors, the transportation as well as the industry. Synthetic Natural Gas has been assumed to be the chemical energy carrier as well as the energy storage medium. The 1759 TWh energy demand is going to be supplied by wind (655 TWh), other renewables (951 TWh) and electricity import (153 TWh). In order to supply 655 TWh wind

energy, around 52,000 wind turbines of 5 $MW_{nameplate}$ power are needed; another 30,000 might have to be incorporated into an SNG-based system for long-term energy storage needed for national security. The wind-turbines have to be incorporated into a complex system involving water electrolysis, methanation and Gas Turbine Steam-Cycle processes.

A regional-area-unit with full-energy-provision using alone wind energy, which we name as Exclusively Green Energy Community (EGEC), has been proposed as an important mile-stone. Such a community of around 3400 inhabitants living on an area of around 15 km^2 would require 105 GWh of end-user energy. The community would need to operate ten wind-turbines of 5 $MW_{nameplate}$ power each, hydrolysis and methanation plants as well as storage sites for SNG, oxygen, hydrogen, and carbon-dioxide. Such an energy system also incorporating transmission grids, electrical batteries, pipe-lines, and storage sites would have to be intelligently controlled to secure continuous and adequate provision of energy with options for providing up to 30% of the energy as SNG. Realizing the complexity of such a system, demo projects of this nature have to be initiated.

It is clear that due to dimensions of the tasks, the Energiewende will last for several generations and perhaps even for a century or two. Realization of this overwhelming national venture has to proceed through milestones and demonstration projects. Experience gained during operating Exclusively Green Energy Communities (EGECs) is going to be of a crucial value, since it would be a confirmation that communities can function as self-sufficient energy units.

The list of technological developments needed for this complex national venture is long and includes a wide spectrum of technologies. Many of them, in their current development stage, are not ready for implementation and incorporation even into small-scale EGECs, not to mention cities or lands. Progress has been made over the last two decades or so in all the technologies listed; however in the current development stage they do not belong to standard "on the shelf" technologies which can be easily configured into self-sufficient green energy systems. Germany's current buy-in for the energy change programme may diminish since the goals are being continuously repeated without appreciating the scale of the venture and setting clear, achievable milestones.

Aftermath

The aim is to underline both the scale and technological complexity of the national German Energiewende programme "from fossil fuels to renewables". Some of the arguments presented in this paper have already been brought forward [40–42]. While writing this paper, we have refrained from any considerations on the foreseen costs and no attempts have been made to estimate the "green energy" prices. A thorough analysis "from the cradle to the grave" of the considered energy technologies has to be carried out to estimate energy return on energy investment factors for various energy technology options considered.

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